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RESULTS OF LANDING TESTS OF VARIOUS AIRPLANES

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SUMMARY

For several years the National Advisory Committee for Aeronautics has been conducting an investigation of the landing characteristics of representative airplanes with particular reference to the problem of landing-gear design. Results of this investigation, which has included airplanes ranging in gross weight from approximately 1000 to 50,000 pounds and in span from 28 to 149 feet, are presented. Some blind landings, and also day and night service landings, were included in the program. The conditions imposed upon an airplane during a landing, as determined from experience with the 21 airplanes tested, and the ground reactions produced as a result of these landing conditions are also outlined and discussed.

The maximum vertical velocities attained by the airplanes in conventional landings ranged as high as 10 feet per second for the lighter airplanes and diminished as the airplane weight increased until a value of about 5 feet per second was encountered with the largest airplanes. In blind landings, vertical velocities as high as 13 feet per second were obtained. On the basis of the data for all the landings, a vertical velocity of 2 or 3 feet per second may be termed a "normal" conventional landing velocity for all the airplanes tested.

The aerodynamic support of the wings at the instant of ground contact, which ranged from 0.6 to 1.0 times the airplane weight, was subtracted from the total airplane vertical load factor in order to obtain the landing-gear vertical load factor. The landing-gear maximum vertical load factors for conventional landings approached a value of 4 for the lighter airplanes and a value of 1 for the heavier airplanes. For blind landings with two of the heaviest airplanes, a landing-gear vertical load factor of about 2 was experienced. Based upon a consideration of all the landings, a landing-gear vertical load factor of 1 may be termed normal for conventional landings with all the airplanes tested.

As the loads produced due to a landing impact under any given set of landing conditions depend upon the design of the shock-absorbing equipment, it is suggested that landing-gear design be directed toward the production of equipment capable of meeting prescribed landing conditions rather than toward capacity for carrying some specified load.

INTRODUCTION

When the landing of aircraft is studied for the purpose of determining proper landing-gear design, two distinct subjects must be considered. The first is the determination of the conditions to which the airplane may be subjected during the landing and the second is the determination of the airplane loading produced as a result of these conditions. Because of lack of knowledge concerning landing conditions and because data on landing loads can be used directly, landing-gear design at present is usually based upon loads experienced with airplanes similar to the one under consideration.

A program of landing investigations has been conducted by the NACA at the Langley Memorial Aeronautical Laboratory, Langley Field, Va., for the purpose of increasing the existing knowledge concerning landing conditions and resulting loads. These investigations were undertaken at the request of the Army Air Corps, the Bureau of Aeronautics, and the Civil Aeronautics Authority; they were carried out, in general, as a secondary study upon airplanes that had been made available by these agencies for research of a different kind. As a result, considerable data in regard to airplane type and size were accumulated, but the extent of each investigation was limited, for most of the airplanes, to about 15 to 20 landings of varying severity within the pilot's discretion.

For the majority of the airplanes, the data obtained were confined to vertical and horizontal velocity, longitudinal attitude, and pitching accelerations as well as accelerations perpendicular and parallel to the thrust axis. In a few cases more data were secured, and for one airplane the vertical velocity and the attitude at contact were determined for some 200 landings.

Because the loading of the airplane for a given landing depends considerably upon the characteristics of the landing gear, it appears most logical to base landing-gear design upon landing conditions. Landing conditions were therefore given as much attention in the investigation as loading conditions.

APPARATUS AND TESTS

The principal characteristics of the airplanes used in the investigation are shown in table I. Throughout this paper the number used to designate an airplane corresponds to the number assigned to that airplane in table I. In general, the instruments installed in the airplanes for the landing tests included a two- or a three-component recording accelerometer, one or two angular velocity recorders, an airspeed recorder, and a timer. In each case the accelerometer was mounted as near as possible to the center of gravity of the airplane and was usually oriented to record directly the accelerations parallel to the principal airplane axes. Angular pitching and rolling accelerations were determined by graphical differentiation of the records of the corresponding angular velocities. In one series of tests, two control-position recorders were mounted on the landing gear and were arranged to record the position of each of the main wheels relative to that of the fixed portions of the struts. The timer provided timing marks on each record and also, by operating solenoids in all the instruments simultaneously, provided a means for synchronizing the records.

The attitude angles and the linear displacements of the airplanes were determined from the records obtained with one of the NACA recording phototheodolites set up on the landing field 600 to 1500 feet from the landing runway, depending upon the size of the airplane tested. The attitude angles were calculated from the records with the aid of reference points on the airplanes or of reference lines painted on the sides of the fuselage. In most of the cases, alternate segments of the main wheels were painted in contrasting colors so that the frame in the phototheodolite record in which rotation of the wheels began could easily be determined. The beginning of rotation of the wheels was taken as an indication of the time of the first contact with the ground. Synchronization of the phototheodolite records with the flight instrument records was effected by correlation of the frame in which the first ground contact occurred with the points on the instrument records at which sharp breaks in the record lines indicated the beginning of the first impact.

Horizontal and vertical velocities of the airplane at contact were determined by graphical differentiation of time histories of the corresponding displacements. The surface wind velocity at a height of 6 feet above the ground was measured by means of an integrating anemometer, or a vane-type wind-velocity indicator. The approximate airspeed of the airplane was calculated from the horizontal velocity and the velocity of the surface wind.

The principal factors investigated for the various airplanes are given in table II. For each airplane the tests consisted of a series of landings of varying severity. For a majority of the airplanes an attempt was made to achieve, in one or more landings, the highest vertical velocity consistent with safety. The pilot's judgment was accepted concerning the magnitude of the vertical velocity that the airplane could withstand. Variations in the contact velocity were secured by varying the instant at which the landing flare (leveling off) was started and by employing whatever power the pilot felt necessary.

In order to determine the forces developed in unsymmetrical impacts, one-wheel landings were made with several of the airplanes. Tail-first landings were made with a majority of the airplanes equipped with conventional-type landing gear. One nose-first impact was made, with considerable difficulty, with one of the airplanes equipped with tricycle landing gear.

The data for one of the airplanes, a single-place pursuit type, airplane 13, obtained in the usual manner from flight tests made by one of the NACA test pilots were supplemented by a statistical study of routine service landings of airplanes of the same design under various conditions by Army pilots, singly and in formation, by day, and by night with the aid of landing flares. Similarly, the data obtained in ordinary landings of airplanes 19 and 20 were supplemented by an investigation of the landing conditions and the resulting ground reactions experienced in "blind" or instrument landings of these airplanes. The symbols, assumptions, and equations used in calculating the ground reactions are presented in the appendix.

RESULTS AND DISCUSSION

The two important design considerations that exist in any airplane landing are the landing conditions to which the airplane is subjected and the loads resulting from these conditions. Although consideration of loads experienced has been used by the majority of designers, the load factor achieved in any given landing is greatly affected by the characteristics of the landing gear and, by equipping a given airplane with various gear, different load factors can be obtained for the same landing condition. For this reason, the discussion of results has been divided into two parts; namely, a presentation of the landing conditions and a corresponding presentation of the loads experienced.

The airplanes investigated will be considered under the following weight classifications:

Class	Type of airplane	Weight (lb)
I	Light	Up to 3,000
II	Medium	3,000 to 10,000
III	Heavy	Over 10,000

OBSERVED LANDING CONDITIONS

Attitude.- If the angle between the thrust axis and the ground plane at the instant of ground contact is considered first, the test results may be divided somewhat roughly into four divisions, namely:

	Attitude angle (deg)
Class I	-4 to 13.5
Classes II and III	4 to 16
Blind landings, class III	-4.5 to 5
Airplanes with tricycle landing gear . . .	-5 to 15

Numerical values were not obtained for the lateral and directional attitudes encountered. Landings were observed, however, during which the inclination of the lateral axis was great enough to cause one wheel to absorb the complete initial shock.

Vertical velocity.- The maximum vertical velocity at impact recorded for each of the airplanes tested is plotted against airplane weight in figure 1. The numbers correspond to the order in which the airplanes are listed in table II, which also gives the number of landings for each airplane. For most of the airplanes, attempts were made to secure as high vertical velocities as possible, the pilot's judgment being accepted as to whether the airplane could withstand further shock. Because the test pilots did attempt to cover a large range of types of landing and because they were all experienced, the many landings previously made by these pilots serve as a statistical background for figure 1. Landing records of some 100 day and night service landings with airplane 13, during which the pilots were unaware that they were under observation, did not produce any data that would affect figure 1.

The curve ABC in figure 1 represents the vertical velocity to be expected in a severe conventional landing. An examination of the data for all the landings, including such sources as pilots' and observers' notes, leads to the conclusion that a vertical velocity of 2 or 3 feet per second comprised a normal conventional landing for all the airplanes tested.

In order to obtain a clear picture of the significance of figure 1, what the pilot is attempting to do in landing an airplane must be considered. Stated briefly, his task is to achieve, if possible, zero vertical velocity at ground contact by choosing some instant at which to start the landing flare and then employing whatever degree of control and power he considers necessary to achieve his aim. Figure 1 indicates the maximum departure from the ideal of zero vertical velocity produced during the landings by variations in piloting technique or by factors beyond the pilot's control.

In practically all landings the pilot flares the airplane more than is necessary, although occasionally landings are made with insufficient flare. In the vast majority of landings, the amount of excess flare is purely a matter of piloting technique. The vertical velocity that results, however, is governed by a combination of piloting ability and airplane characteristics. If the airplane has been leveled off at a height above the ground up to as high as 10 feet, its rate of descent will depend upon the amount of lift that can be retained, and this quantity depends upon the wing characteristics and the pilot's ability to control them. Two important wing characteristics involved are the loss of lift on the wings when they are stalled and the rolling or pitching produced.

The amount of lift maintained until the instant of ground contact varied for the different airplanes but, in general, the airplanes with wings of rectangular plan form retained considerably more lift than those with tapered wings. As a result, the pilots flared the airplanes of class I at a height of about 5 or 6 feet above the ground in order to obtain the maximum velocities of figure 1. Velocities of similar magnitude were obtained with several airplanes of class II by stalling only 2 feet from the ground.

The combined effect of high lift-loss, rolling after stall, and piloting experience produces the decrease with increasing airplane weight in the envelope curve ABC of figure 1. The airplanes in class III all had tapered wings with high lift loss usually accompanied by rolling. The experienced test pilots were aware of these facts and, because of their increased sense of responsibility with such large airplanes, they used power in landing.

Although the preceding discussion has dealt mainly with the type of landing in which the pilot employs more flare than is necessary, the type with insufficient flare was included in the tests and was responsible for some of the test points in figure 1. The best examples of landings with insufficient flare, or none at all, are blind landings. In the Army system of blind landing, no flare is used and the attempt is made to hold a constant rate of descent of 6 feet per second. In figure 1 it is of interest to note that vertical velocities obtained in blind landings were very close to 6 feet per second greater than values obtained from the curve representing maximum deviation from the goal of zero vertical velocity set for conventional landings.

<u>Pitching velocity</u>.- The actual value of the pitching velocity was not computed in every landing, but a careful inspection of the records leads to the conclusion that a value of ±0.4 radian per second is a reasonable limit for landings with conventional-type gear.

For the airplanes equipped with tricycle-type landing gear, difficulties were encountered in making a nose-wheel-first landing with the two airplanes tested and only one such landing was obtained, but the possibilities of obtaining this type of landing might have been increased had the pilots been more familiar with tricycle landing gear and had other airplanes, with a different relation between landing-gear geometry and wing incidence, been tested. For airplane 6, the maximum negative pitching velocities at the instant of ground contact were approximately 0.8 radian per second and for airplane 16, approximately 0.6 radian per second. For one landing with airplane 16, which had a rapid response to elevator change, a negative pitching velocity of -1.33 radians per second was produced by employing special technique. The resulting energy of rotation of the airplane was equivalent to the kinetic energy of translation of a velocity of 10 feet per second.

Rolling velocity.- The rolling velocity at contact can reach an appreciable value and should probably be considered as contributing to the loads involved in single main-wheel impacts. High rolling velocities were generally developed only for airplanes subject to unsymmetrical or wing-tip stalling.

The rolling velocities encountered were approximately the same for conventional landings, with both types of landing gear, and for blind landings. The test results revealed a lower rolling velocity at contact for the larger airplanes, these results confirming those of flight tests of flying qualities, which usually indicate more sluggish action with the larger airplanes. On the basis of the data secured, single-engine airplanes seldom exceeded a rolling velocity of 0.5 radian per second at the instant of ground contact; an equivalent figure for two- and four-engine airplanes was 0.3 radian per second.

Because of the location of the nose wheel or the tail wheel in the plane of symmetry of the airplane, they are not appreciably affected by rolling during landing. Single main-wheel impacts are often due, however, to rolling immediately prior to contact, and it appears questionable whether the increase in energy due to rolling can be neglected for landings of this type.

Lateral velocity, or side drift.- Because the landing tests were a secondary investigation, as has been mentioned, the lack of necessary instruments and time required for side-load investigations resulted in few data being obtained on the subject of lateral velocity. With two of the airplanes, a few landings were made in a cross wind of 10 miles per hour. The pilot, exercising control to maintain the airplane in a level attitude, slipped into the wind and decreased his lateral ground speed to a value of approximately 2 feet per second. For these two airplanes, and also for a few other airplanes equipped to record side loads but not purposely landed with side drift, the lateral forces encountered were small and well below present design values.

The determination of design conditions for a side-drift landing, or the determination of design side loads themselves, appears to be a difficult problem. The process of equipping an airplane to record side forces and then attempting landings until a design limit force is decided upon is too hazardous and uncertain to be feasible. Furthermore, the design limit force so established would be of minor value unless it could be correlated with lateral velocity and airplane direction. In fact, lateral velocity and airplane direction, which establish the side-drift landing conditions, are probably more important than the force because, if the conditions can be set, the forces may be determined more safely in a laboratory. The lateral velocity could be determined by proper use of phototheodolites, or by photographing the ground from a camera fixed beneath the airplane, but both methods have operational difficulties, and flight investigations become hazardous as the lateral velocity increases. It is quite possible that a reasonable limit for lateral velocity could be based upon present experience without further tests.

LANDING-GEAR LOADS MEASURED DURING THE TESTS

Vertical loads, main and nose wheels.- The ratio of the maximum vertical impact force on the landing gear recorded for each of the airplanes tested to the weight of the airplane as flown has been plotted against the vertical velocity at contact in figure 2(a). (Symbols used on the figures in this paper are defined in the appendix.)

Considerable scattering of the data is to be expected because, as has been previously mentioned, the maximum load resulting from a landing at a given vertical velocity is determined by the characteristics of the shock-absorbing system employed. This effect was evaluated roughly by a comparison of the landing-gear vertical load factors developed by the different airplanes for an assumed vertical velocity of 6 feet per second. The load factors were taken from the load-factor-vertical-velocity curves that were plotted for each airplane, and this approximate "stiffness" relationship is given in table III. The individual airplanes of classes I and III conform to a fair degree with the other airplanes in their classes, but the airplanes of class II apparently have landing-gear systems differing considerably in stiffness. Airplane 20, having a load factor of 1, may be taken as a basis for comparison.

The data plotted in figure 2(a) and the information available in the pilots' and observers' notes indicate that a vertical load factor of 4 for the landing-gear main wheels may be termed a severe landing, and that a vertical load factor of 1 for the main wheels may be termed normal for conventional landings with the airplanes tested. Because the lift of the airplane at the instant of ground contact was approximately 0.8 of the airplane weight, the total vertical load factor for a conventional landing with the airplanes tested was about 2. The fact that none of the large airplanes experienced a landing-gear load factor greater than 2 is to be expected because lower vertical velocities are frequent with these large airplanes. The largest landing-gear load factor for a blind landing was attained with airplane 19, but the value of 1.93, shown in figure 2(a), was undoubtedly exceeded during the tests because the vertical velocity for the landing shown in figure 2(a) was about 8 feet per second while the maximum vertical velocity recorded for airplane 19 in a blind landing was 13 feet per second (fig. 1).

The maximum vertical nose-wheel load encountered in a three-point landing was greater than the maximum nose load produced by main-wheel impact followed by pitching forward upon the nose unit. Too few data were available, however, to indicate whether the type of loading in a three-point landing is more serious than a condition of nose-wheel-first impact. It appears that the possibility of a nose-wheel-first blind landing should be considered. In figure 2(a), the load factor of 1.06 for the nose wheel of airplane 16 was the result of a three-point landing combined with high negative pitching velocity.

Comparison of figures 1 and 2(a) shows that the maximum vertical load did not always occur in the landing of the greatest vertical velocity. An incomplete explanation of this fact is the effect of lateral attitude upon the force developed. A survey of the test data indicated that, for a given vertical velocity at contact, the normal acceleration recorded at the center of gravity of the airplane increased as the time interval between ground contact of the two main wheels decreased, reaching a maximum under the condition of simultaneous contact of the wheels.

In order to investigate the distribution between the two wheels of the total vertical force developed in a definite one-wheel landing, control-position recorders were placed upon each landing strut of airplane 14 and time histories of the vertical motion of the wheels relative to the fuselage were obtained. Several one-wheel landings, during which the force on this wheel reached a maximum and started to decrease before the other wheel made contact, were recorded. An attempt was made to compare the vertical forces resulting from these definite one-wheel impacts with those resulting from exact two-point impacts. The comparison indicated that the single-wheel forces developed were approximately two-thirds as great as the sum of the forces developed on both wheels under the condition of simultaneous contact. This result does not agree with the conventional assumption that the single-wheel force in a one-wheel landing is half of the total force in a laterally level landing of equal vertical velocity. An explanation may be based in part upon the existence of considerable rolling velocity at the instant of contact in a majority of the one-wheel landings. The difficulty of securing symmetrical two-point landings and definite one-wheel landings limited the available data for these types.

Horizontal loads, main and nose wheels.- The ratio of the maximum rearward force on the landing gear recorded for each airplane during a landing impact to the weight of the airplane as flown has been plotted against vertical velocity at contact in figure 2(b). The scattering of the points is pronounced, as might be expected, because in such a plot many factors involved in determining the rearward ground reaction are neglected.

Although the maximum vertical and the maximum rearward forces frequently occurred together, the number of landings for which this type of loading did not occur indicated that the assumption of simultaneously occurring maximums for all designs would impose an unnecessarily severe loading consideration on some airplanes. Some understanding of the development of the friction force between the tires and the ground, and especially the relationship between this friction force and the vertical force, was considered desirable. The following analysis is an attempt to provide that understanding.

In order to discuss more clearly the relation that exists between the normal and the horizontal decelerating forces during the first impact, attention is directed to a time history of these forces (fig. 3). For practically all of the landings, the increase in the forces during the time interval Δt_x was approximately uniform, as shown by straight lines AB and DE. The data are not sufficiently conclusive, however, to insure that the friction coefficient is exactly constant. (Data in reference 1 indicate that the coefficient of friction is almost independent of slippage until this slippage is reduced below 10 percent, whereupon the coefficient rapidly approaches zero.) Apparently the wheels rotate and slide during the period Δt_x, but at E the wheel peripheries reach a velocity equal to more than 90 percent of the airplane ground speed, after which the decelerating force becomes practically negligible.

If it is assumed that the vertical load increases uniformly over the period Δt_z and that the coefficient of friction remains constant until the peripheral velocity of the wheel reaches the ground speed of the airplane (at which time it drops to approximately zero), the value of the maximum decelerating force for any one wheel may be found from the relation

$$F_{h_{max}} = \frac{1}{r_e}\sqrt{\frac{2I_w V_h \mu F_{v_{max}}}{\Delta t_z}} \qquad (1)$$

where

$F_{h_{max}}$ maximum rearward horizontal force that acts on wheel, pounds

r_e effective rolling radius of wheel under impact loading, feet

I_w moment of inertia of wheel, slug-feet square

V_h ground speed of airplane at time of contact, feet per second

$F_{v_{max}}$ maximum vertical force on wheel, pounds

μ coefficient of friction

Δt_z time interval elapsing between first ground contact of wheel and attainment of maximum vertical force on wheel, seconds

It was decided to check the validity of equation (1) after a blind landing with airplane 19 had resulted in a rearward ground reaction exceeding the weight of the airplane. Consequently, the moment of inertia of one of the wheels of airplane 19 was measured by raising the wheel and attaching a cord to the tire tread, wrapping the cord several times around the wheel, and using a falling weight to unwrap the cord and thus rotate the wheel. The moment of inertia so determined was 12 slug-feet square. The actual weight of the wheel was found to be 276 pounds. The values of $F_{v_{max}}$, V_h, and Δt_z were obtained from records of the landing in question, and the quantities r_e and μ were assumed. Substitution of these values in equation (1) resulted in a maximum rearward horizontal force slightly greater than the weight of the airplane. These calculations, therefore, confirmed the measured value of the rearward ground reaction and proved the fundamental soundness of equation (1).

A further indication that the decelerating force in a landing is strongly affected by wheel rotation is the fact that this force is almost negligible during second impacts, for which the wheels are already "up to speed." The use of devices to cause wheel rotation prior to ground contact would undoubtedly reduce the decelerating force considerably, thereby alleviating the serious problem of tire maintenance.

The value of the coefficient of friction μ varied during the tests from 0.2 to 1.0, the maximum value being recorded for landings on dry concrete. Although it is possible that the brakes may have been applied prior to contact in a few cases, such application was not intentional because in a so-called braked landing the pilot normally withholds application of the brakes pending the results of the initial shock. The calculated values of the coefficient of friction for various landings indicated that the magnitude of this coefficient was mainly a function of the character of the landing surface and was affected only slightly, if at all, by the degree of wheel rotation existing, provided that some sliding was still present. The seriousness of a landing made with brakes set prior to ground contact lies not in the magnitude of the friction coefficient to be expected (because coefficients just as large can be the result of wheel inertia in unbraked landings) but in the presence of a large friction coefficient at the time of maximum vertical force.

Tail loads.- The vertical force acting upon the tail wheel or skid could be calculated only for those airplanes whose moments of inertia about the lateral axis were known. This requirement confines the data on tail load to five airplanes, all falling in class II. Of these, three experienced a vertical tail load factor of approximately 0.3, one a factor of 0.6, and one a factor of 1.0. The rearward forces upon the tail wheel were not measured but were assumed equal to the product of the corresponding vertical force and the coefficient of rolling friction. For swiveling tail wheels the lateral ground reaction may reasonably be assumed negligible.

Lateral loads.- The instrument installation in the majority of the airplanes tested did not provide for the measurement of accelerations parallel to the lateral axis. This fact, together with the previously mentioned difficulty of obtaining landings with appreciable lateral ground speed, limited the data available. The maximum landing-gear lateral load factor experienced in the first impact occurred in a one-wheel landing with airplane 1 and reached a value equal to one-half the airplane weight. For the rest of the airplanes investigated (all below 7000 lb in weight), the maximum landing-gear lateral forces, which average approximately one-third the airplane weight, occurred while taxying.

As the lateral loads encountered in taxying were greater than any observed during a landing, the possibility that taxying may determine the design side load should be considered, especially where ground looping may be encountered. From discussions with pilots and observations of many landings, it appears that the present design lateral loads are sufficient for the vast majority of landings and that almost all cases of landing-gear failure due to side loading are caused by ground looping. Whether or not an airplane should be designed to withstand a ground loop and what magnitude of ground loop should be considered the design case are questions requiring an answer, if the possibility of basing design side loads on this condition is to be considered.

Taxying.- The vertical forces on the landing gear during taxying were recorded for 13 of the 21 airplanes tested. The maximum landing-gear vertical load factors for taxying and for landing impacts are compared in figure 4. Logarithmic paper was used for the plot because of the large variation in airplane weight. For airplanes of class I the taxying loads were of the same order of magnitude as the landing impact loads. For class II the impact loads were, with a single exception, appreciably greater than the taxying loads. For class III the taxying loads were greater than the impact loads for normal landings, and taxying thus becomes a factor of considerable importance for ordinary operation of airplanes of class III.

Because the taxying load is similar to the landing impact load in its dependence upon the shock-absorbing characteristics of the landing gear, the desirability of establishing some design condition that can be applied to each airplane to represent application of the limit taxying load is evident. The acceleration produced by application of the test condition would then be investigated to see if it were an important design consideration. One suggested procedure is the determination of an "equivalent" vertical velocity that would represent, in a drop test, the imposition of the limit taxying load. The taxying operation of the landing-gear system would have to be considered in such a test. A simpler solution to the problem might be to use the taxying forces to be expected as a minimum limit for design, and a study of figure 4 would suggest a load factor of 2 for all three airplane classes.

A description of the condition of the surface of the field used in the taxying runs would be more or less relative, but no attempts were made to roll over unusually rough ground. The maximum rearward loads occurring during ground runs varied from 10 to 70 percent of the weight of the airplane, but in no case did these loads exceed the maximum values obtained in landing impacts. The lateral forces that occurred during taxying have already been discussed.

CONCLUSIONS

1. A vertical velocity of 2 or 3 feet per second and a landing-gear vertical load factor of 1 may be considered as normal for conventional landings with any of the airplanes tested.

2. In conventional landings the maximum vertical velocity at contact ranged from 10 feet per second for the lighter airplanes to 5 feet per second for the heavier airplanes; the maximum vertical load factor imposed on the landing gear ranged from 4 for the lighter airplanes to 1 for the heavier airplanes.

3. In blind landings vertical velocities as high as 13 feet per second were obtained. With two of the heaviest airplanes landing-gear vertical load factors of about 2 were experienced in the blind landings.

4. In the design of the landing gear the shock-absorbing equipment and its supporting structure should be considered as a unit to be subjected to specified landing conditions. This procedure is preferable to the conventional method of designing the structure for a specified load factor.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
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APPENDIX

CALCULATION OF GROUND REACTIONS

Symbols

The significance of the symbols used in the calculation of the ground reactions is as follows:

W weight of airplane as flown

a_{z_g} component of recorded acceleration at center of gravity that is perpendicular to ground (positive upward)

a_{x_g} component of recorded acceleration at center of gravity that is parallel to ground (positive rearward)

a_r resultant acceleration $\left[\left(a_{x_g}{}^2 + a_{z_g}{}^2\right)^{\frac{1}{2}}\right]$

Zero subscripts are employed to indicate the accelerations at the instant of the first ground contact.

t_o instant of first ground contact

Δt_z time interval elapsing between first ground contact and attainment of maximum vertical acceleration (also referred to as "equivalent quarter-period" of impact)

Δt_x time interval elapsing between first ground contact and attainment of maximum horizontal acceleration

F_{z_g} total vertical component of ground reaction during interval Δt_z (positive upward)

F_{x_g} total rearward component of ground reaction during interval Δt_z (positive rearward)

F_{w_v}, F_{t_v}, and F_{n_v} vertical forces on main wheels, tail wheel, and nose wheel, respectively (positive upward). Note that F_{w_v} is sum of main-wheel forces

F_{w_h}, F_{t_h}, and F_{n_h} horizontal forces on main wheels, tail wheel, and nose wheel, respectively (positive rearward)

x_w, x_n, and x_t horizontal distance from center of gravity to main wheels, nose wheel, and tail wheel, respectively

z distance of center of gravity above ground

dq/dt pitching acceleration, positive for nose up

dp/dt rolling acceleration, positive for right wing down

I_y moment of inertia of airplane about its lateral axis

The application of the symbols relating to linear acceleration is illustrated in figure 3, which shows typical time histories of the vertical and horizontal accelerations experienced in the first and second landing impacts of a severe unbraked landing of a large Army bomber.

Derivation of Equations

In the reduction of the instrument data, certain assumptions were necessary for the calculation of the ground reactions occurring during the principal landing impacts. In all cases it was assumed that the airplane reacted as a rigid body and that the accelerations recorded by an instrument mounted at the center of gravity were those of the structure as a whole. The validity of this assumption is conditioned to some extent by the experience of the observer and his judgment in the interpretation of the instrument records. The structural rigidity of the airplanes tested was such that a satisfactory interpretation of the records was possible in all but a few of the tests. It was also assumed that the aerodynamic forces on the airplane do not change appreciably during the small time interval elapsing between the occurrence of the first ground contact and the attainment of the maximum vertical acceleration.

On the basis of this last assumption, for all impacts:

$$F_{z_g} = (a_{z_g} - a_{z_{g_o}})W \tag{2}$$

$$F_{x_g} = (a_{x_g} - a_{x_{g_o}})W \tag{2a}$$

In a one-point impact (tail-first landing, nose-first landing, or single main-wheel landing)

$$F_{t_v},\ F_{n_v},\ \text{or}\ \ F_{w_v} = F_{z_g} \tag{3}$$

$$F_{t_h},\ F_{n_h},\ \text{or}\ \ F_{w_h} = F_{x_g} \tag{3a}$$

For the purposes of this report, landing impacts are classed as one-point if the vertical force on the single wheel or skid involved reaches a maximum value before any other point of the airplane touches the ground. In the case of a landing with simultaneous ground contact of the main wheels, the vertical and horizontal loads as given by equations (3) and (3a) must be divided equally between the two wheels. For landings falling between one point and simultaneous impact of the main wheels, equations (3) and (3a) will give the totals of the horizontal and vertical forces acting without any indication of their distribution. For these nonsymmetrical main-wheel landings, the distribution of the forces between the two wheels may be found if the angular rolling acceleration and the moment of inertia of the airplane about the X axis are known. In the present investigation, angular rolling velocities were measured in only a few cases, and therefore very few data are presented concerning the distribution of forces in such landings.

In three-point impacts, only the sums of the forces on the three wheels may be found unless the moments of inertia of the airplane are known. If the moment of inertia in pitch is known, the equation for conventional landing gear may be written:

$$F_{w_v} = \frac{F_{z_g} x_t + F_{x_g} z + I_y \frac{dq}{dt}}{x_w + x_t} \tag{4}$$

In this equation it is assumed that the rotational moment of inertia of the tail wheel is so small that the horizontal component of the tail-wheel load is negligible. The vertical force on the tail is given by

$$F_{t_v} = F_{z_g} - F_{w_v} \tag{5}$$

For tricycle landing gear in three-point impacts,

$$F_{w_v} = \frac{F_{z_g} x_n - F_{x_g} z - I_y \frac{dq}{dt}}{x_w + x_n} \tag{6}$$

$$F_{n_v} = F_{z_g} - F_{w_v} \tag{7}$$

It has been suggested that one critical type of loading of the nose wheel of an airplane equipped with tricycle landing gear occurs in a nose-high, fully braked landing, in which high rotational velocities are built up about the main wheels. If it is assumed, in a manner similar to that already explained in connection with main-wheel impacts, that the aerodynamic and main-wheel forces on the airplane do not change appreciably during the time interval between nose-wheel contact and attainment of maximum force on this wheel, it follows that the changes in the vertical, the horizontal, and the angular pitching accelerations are caused by the nose-wheel loads; and it is possible, by equating the moments about the main wheels, to write for the vertical force on the nose wheel

$$F_{n_v} = \frac{\Delta F_{z_g} x_w + \Delta F_{x_g} z + I_y \Delta\frac{dq}{dt}}{x_n + x_w} \tag{8}$$

The calculation of the distribution of the horizontal force in three-point impacts with tricycle landing gear is complicated by the fact that the rotational moment of inertia of the nose wheel is considerable and, in fact, for some designs is equal to that of the rear wheels. Experience has shown that large horizontal forces are developed during the initial impact in unbraked landings in bringing the peripheral velocity of the wheels up to the ground speed of the airplane, since the wheels continue to slide until this speed is attained. Airplane 6 was equipped with tricycle landing gear having three wheels of equal size, and in this case the horizontal forces on the main-wheel and nose-wheel units were calculated by assuming the distribution of the horizontal forces to be in the same ratio as that of the vertical forces.

Records of the taxying loads experienced at low speed over rough ground were secured for a number of airplanes. In such cases the aerodynamic lift was estimated and the air-load factor subtracted from the vertical acceleration to obtain the vertical ground reaction.

REFERENCE

1. Moyer, R. A.: Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relation to Highway Safety. Iowa Eng. Exp. Station Bull. 120, vol. 33, no. 10, Iowa State College, Aug. 8, 1934, p. 58.

TABLE I

CHARACTERISTICS OF AIRPLANES TESTED

Number	Airplane	Type (1)	Landing gear (2)	Wing area (sq ft)	Span (ft)	Weight as flown (lb)
1	Piper Cub J3L-50	L,M,hw,1E	C,Fx,Sc	178.5	35.2	950
2	Taylorcraft BC-65	L,M,hw,1E	C,Fx,Sc	167.0	36.0	1,058
3	Aeronca 65-C	L,M,hw,1E	C,Fx,Ol	169.0	36.0	1,090
4	Bellanca 14-9	L,M,lw,1E	C,Re,Ol	161.5	34.2	1,340
5	Stinson 105	L,M,hw,1E	C,Fx,Ol,Sp	155.0	34.0	1,373
6	Hammond Y-1	L,M,lw,1E	T,Fx,Ol,Sp	210.0	40.0	2,075
7	Boeing P-26A	L,M,lw,1E	C,Fx,Ol	149.5	28.0	3,213
8	Boeing YP-29A	L,M,lw,1E	C,Re,Ol	153.8	29.9	3,667
9	North American BT-9A	L,M,lw,1E	C,Fx,Ol	248.3	42.0	4,472
10	Curtiss XF13C-3	L,M,hw,1E	C,Re,Ol	205.0	35.0	4,662
11	Consolidated PB-2	L,M,lw,1E	C,Re,Ol	297.0	43.9	5,280
12	Chance-Vought XSB3U-1	L,B,1E	C,Re,Ol	327.0	{33.5 31.1	5,431
13	Curtiss P-36A	L,M,lw,1E	C,Re,Ol,Pn	236.0	37.3	5,785
14	Chance-Vought SB2U-2	L,M,lw,1E	C,Re,Ol,Pn	305.3	42.0	6,305
15	Northrop A-17A	L,M,lw,1E	C,Re,Ol,Pn	362.0	47.8	6,719
16	Douglas Dolphin OA-4A	A,M,hw,2E	T,Fx,Ol,Pn	540.1	60.0	9,155
17	Lockheed 14-H	L,M,mw,2E	C,Re,Ol,Pn	545.3	65.5	14,700
18	Douglas DC-3	L,M,lw,2E	C,Re,Ol,Pn	987.0	95.0	20,000
19	Douglas B-18	L,M,mw,2E	C,Re,Ol,Pn	958.6	89.5	20,400
20	Boeing B-17	L,M,lw,4E	C,Re,Ol,Pn	1420.0	103.8	39,000
21	Boeing B-15	L,M,mw,4E	C,Re,Ol,Pn	2780.0	149.0	49,700

[1]Symbols for airplane type: L, landplane; A, amphibian; B, biplane; M, monoplane; lw, low wing; hw, high wing; mw, midwing; 1E, single engine; 2E, two engine; 4E, four engine.

[2]Symbols for landing gear: Fx, fixed; Re, retractable; Ol, oleo; Pn, pneumatic; Sp, spring; Sc, shock cord; T, tricycle; C, conventional

TABLE II.- PRINCIPAL FACTORS INVESTIGATED

[x indicates that the value was not determined]

Number	Airplane	Number of landings	Vertical velocity	Horizontal velocity	Recorded air-speed	Attitude of thrust axis	Normal acceleration	Longitudinal acceleration	Transverse acceleration	Pitching velocity	Rolling velocity
1	Piper Cub J3L-50	15									x
2	Taylorcraft BC-65	16							x		
3	Aeronca 65-C	19									x
4	Bellanca 14-9	19									
5	Stinson 105	36									
6	Hammond Y-1	25									x
7	Boeing P-26A	16			x				x		x
8	Boeing YP-29A	30			x				x		x
9	North American Bt-9A	20			x				x		x
10	Curtiss XF13C-3	12			x				x		x
11	Consolidated PB-2	18			x					x	x
12	Chance-Vought XSB3U-1	11							x		x
13	[1]Curtiss P-36A	17									
		147			x		x	x	x	x	x
14	Chance-Vought SB2U-2	45									
15	Northrop A-17A	22			x				x		x
16	Douglas Dolphin OA-4A	16			x				x		x
17	Lockheed 14-H	6							x		x
18	Douglas DC-3	3			x				x		x
19	Douglas B-18	8			x				x		x
	[2]Douglas B-18A	111			x				x		x
20	Boeing B-17	6							x	x	x
	[2]Boeing B-17	47			x				x	x	x
21	Boeing B-15	14							x		x

[1]Service landing.

[2]Blind landing.

TABLE III.- APPROXIMATE RELATIVE STIFFNESS OF SHOCK-ABSORBING SYSTEMS OF AIRPLANES TESTED

Number in text	Airplane	Vertical landing-gear load factor for vertical velocity of 6 ft/sec
1	Piper Cub J3L-50	2.0
2	Taylorcraft BC-65	2.5
3	Aeronca 65-C	2.0
4	Bellanca 14-9	2.2
5	Stinson 105	2.3
6	Hammond Y-1	1.3
7	Boeing P-26A	2.6
8	Boeing YP-29A	3.0
9	North American BT-9A	2.1
10	Curtiss XF13C-3	1.5
11	Consolidated PB-2	2.7
12	Chance-Vought XSB3U-1	1.1
13	Curtiss P-36A	1.5
14	Chance-Vought SB2U-2	1.9
15	Northrop A-17A	2.2
16	Douglas Dolphin OA-4A	1.9
17	Lockheed 14-H	---
18	Douglas DC-3	---
19	Douglas B-18	1.2
20	Boeing B-17	1.0
21	Boeing B-15	1.3

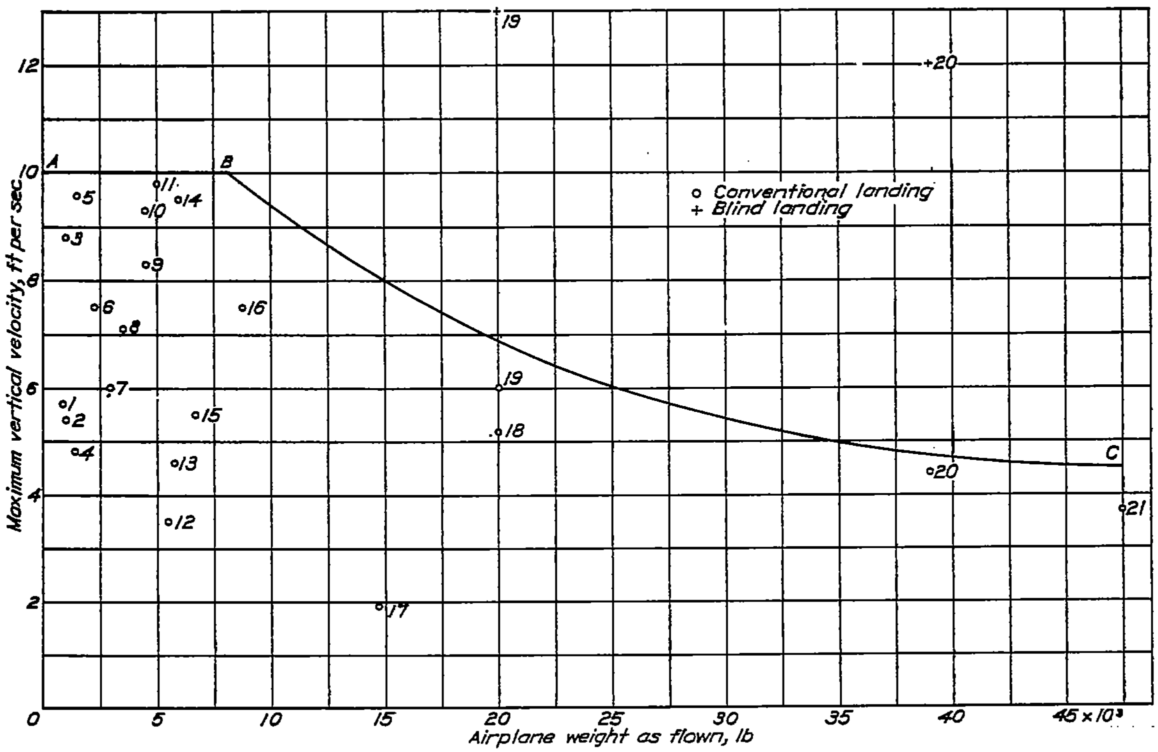
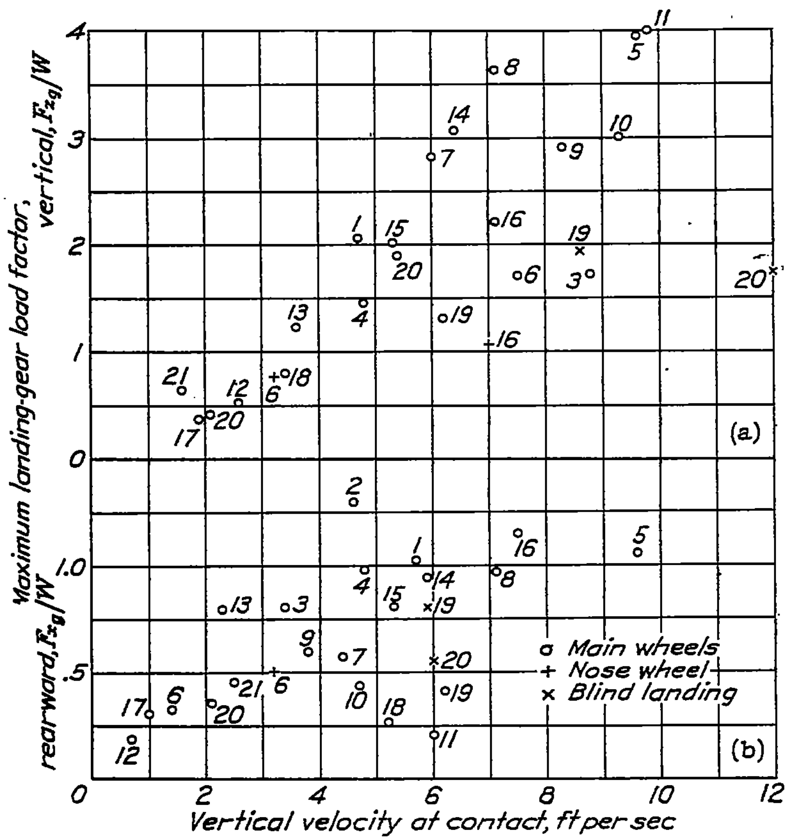


Figure 1.- Maximum vertical velocities experienced by airplanes during landing tests.



(a) Vertical

(b) Rearward

Figure 2.- Maximum landing-gear load factors recorded during landing tests with 21 airplanes.

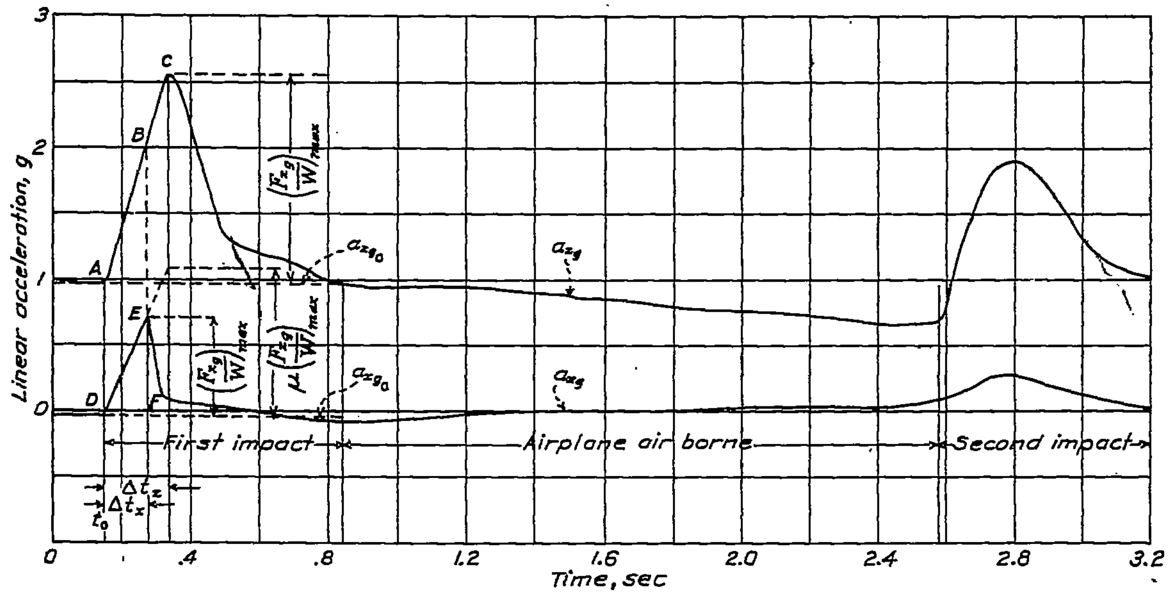


Figure 3.- Linear acceleration experienced in a typical landing.

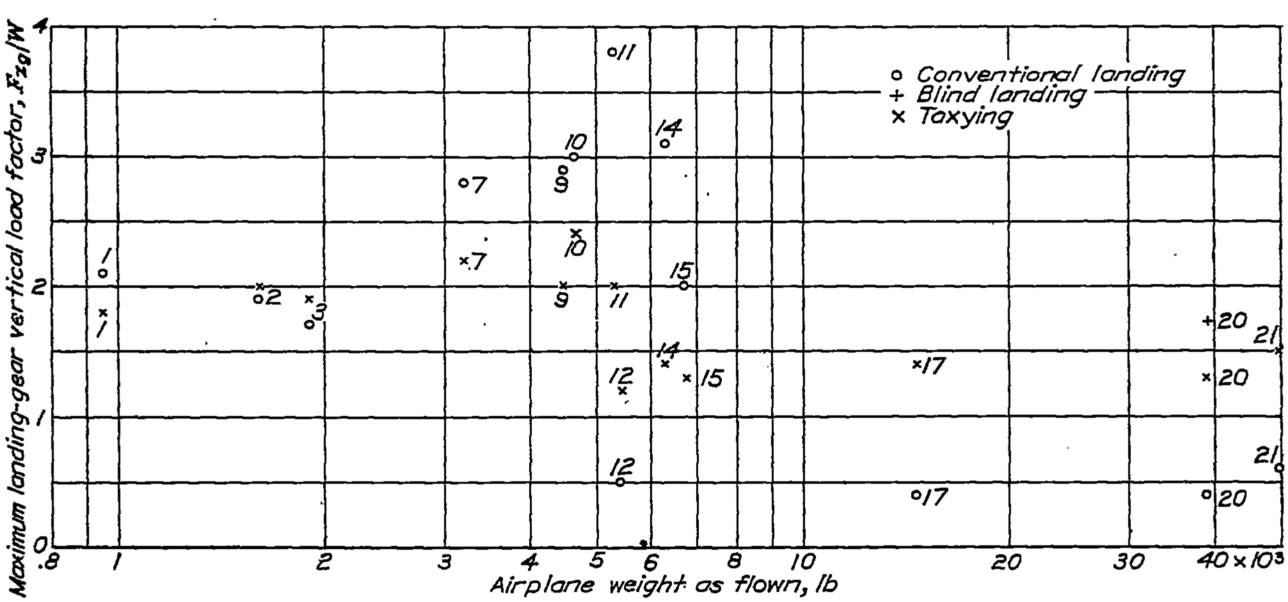


Figure 4.- Comparison of maximum vertical forces due to landing impact and taxying for 13 airplanes.